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Abstract
Piezoelectric transducers are undoubtedly one of the major elements for use in ultrasonic NDE. and our program essentially was involved for the last nine months in what you might call the NDE of NDE transducers, sort of NDE. Hopefully, we're not multiplying two small numbers together here. So, what I'd like to do is just give a summary of what we have been doing and tell you how far up on the learning curve we are.

Disciplines
Materials Science and Engineering | Structures and Materials

PIEZOELECTRIC TRANSDUCERS FOR QUANTITATIVE NDE*

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Piezoelectric transducers are undoubtedly one of the major elements for use in ultrasonic NDE, and our program essentially was involved for the last nine months in what you might call the NDE of NDE transducers, sort of NDE^2. Hopefully, we're not multiplying two small numbers together here. So, what I'd like to do is just give a summary of what we have been doing and tell you how far up on the learning curve we are.

I'll start off by giving a general background on the piezoelectric transducers as we think they're put together... and evaluation of the transducers from experimental results that we have gotten. First, I would like to discuss transducer circuit modeling. The whole idea here is to try to get a very quantitative description of acoustic output versus electrical input and vice versa. We're trying to be particularly careful about the electrical circuit modeling of the piezoelectric element and trying to properly describe how it relates to, not only to media that it's supposed to radiate into, but also the so-called backing that's used to give broad band response.

The terminal measurements on the piezoelectric disk, or electrical terminal measurements,give you some insight into the characteristics of the transducers as far as the transfer function and band width is concerned, but it's really only, a one-dimensional characterization of two-dimensional radiation phenomena. What one must do as well is to step back from the transducer and look at the radiation field pattern. One of the primary reasons for doing this is to establish whether or not the transducer has any flaws in its construction due to disbonding, hot spots caused by the nature of the piezoelectric poling, or any of a number of problems that I have heard about.

Another reason for accurately determining the radiation pattern is that people want to obtain quantitative scattering information from defects and, as indicated in previous papers, this scattering is highly wavelength dependent. The size is going to determine how much signal is reflected back to the transducer, but that, in turn, is going to depend on how much signal gets to the defect, and whether or not you happen to be sitting in one of the near-field nulls on the transducer or someplace out in the far field.

We also are going to look at--we've pretty well set up to do it--the phase information, which in the past has been pretty much neglected. We want to know what the phase front looks like in the radiation field pattern. We also want to know the phase information that's contained in the transfer function from acoustical to electrical. Again, the quantitative response, the transfer function, magnitude and phase, radiation and field pattern as a function of distance in a plane scan perpendicular to the axis of the transducer, are all quantities of interest.

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If you have characterized a given transducer, what you'd like to be able to do, is to use this element at some later time and have some hope that it's going to give you the same type of response. Thus, aging would be a problem, and this apparently has been true with the PZT-type piezoelectric elements. Either the material becomes lower in poling, or something pretty gross happens in terms of a backing or wear plate bond breaking. As far as the piezoelectric activity is concerned, what we thought we'd do is look at single crystal materials. A particular one we looked at was lithium niobate. There are certainly some others available, but lithium niobate seemed to be the more reasonable one to do at the outset. It's coupling coefficient is lower than what one experiences with PZT-type materials, and so one can expect some degradation in band-width. But nevertheless, as a material, it's very well characterized; it's stable, and we should have no trouble with long-term aging. Bond adherence is a problem that would even be associated with the single crystal-type material, and we have some data on what that can do for us.

Concerning band width, we're assuming here that a wide band width is desirable because of the nature of excitation that people have been using, namely very short pulses. You tend to get an impulse response in a rather wide band radiated signal. This may or may not be useful. If you're doing scattering measurements you may appreciate using a tone burst wherein you know something about the frequency content of the radiated waves. In that case, wide band width is not quite so important.

There is probably an interest in having identical transducers, both in frequency response and beam patterns. In terms of available commercial models, this is apparently a pretty tall order. They're identical in all other respects: price, color, etc. The only thing that's not quite the same is how they work. However, we really can't be too critical of the manufacturers on this. After all, they respond to what their major market is, and these transducers have been generally acceptable for the vast majority of the work in the past. Nevertheless, some improvements can be made.

I would like to give a brief review here of how we think transducers might or should be made. I have to admit we haven't had the guts to cut one of the commercial units apart, mainly because of the price, to really see what's inside. But you start off in Fig. 1.1 as simply as possible with a radiating structure composed of a piezoelectric disk placed in a water bath environment. I make a qualification here that you would want to arrange for radial mode damping, and we think that there are ways to do that. Ideally, the transducer impedance would match that of the water. The transducer would be very heavily loaded and give rise to a wide band response. Its radiation would be bidirectional, but you can ignore that if you are clever about placing an absorber behind the disk in the water.

One advantage of this configuration is the elimination of mechanical bonds. Further, if you measured the transducers electrical and acoustical characteristics, you could be very certain that its response would be repeatable. Given the kind of high impedance transducer materials we normally use, it would be a narrow band transducer, because we cannot impedance match the water. But it would be a very reproducible type of device.

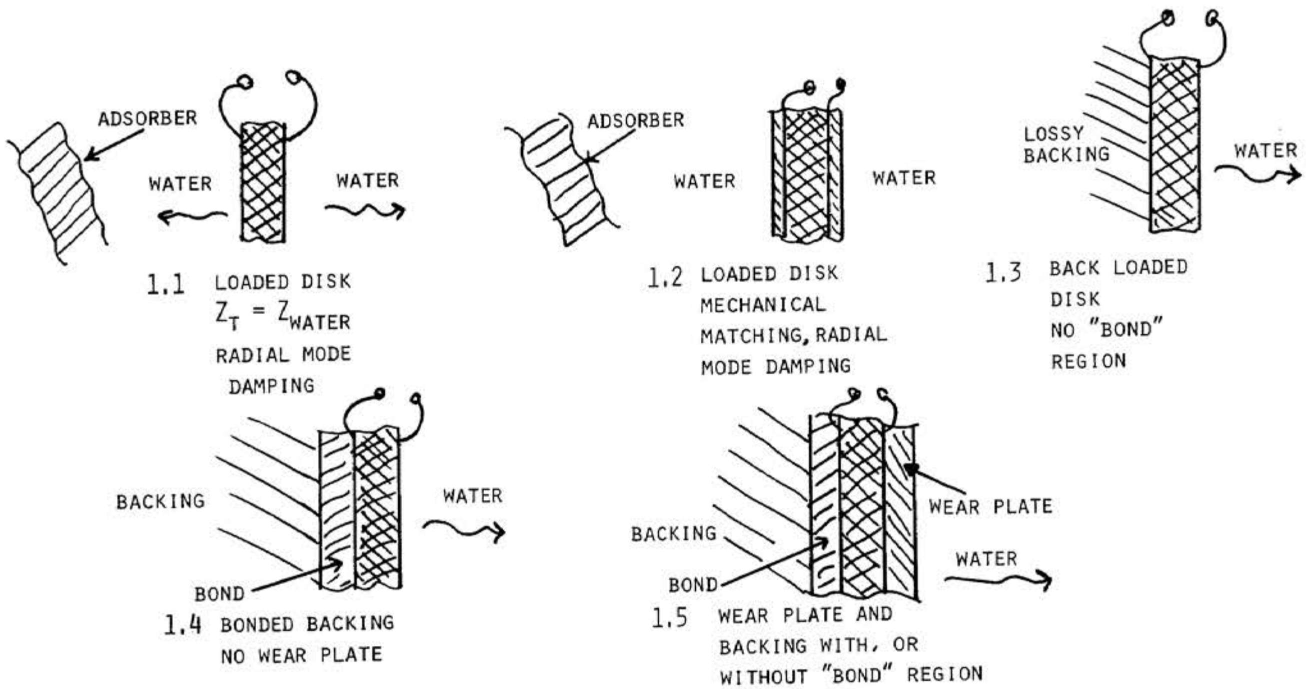

Fig. 1. Transducer configurations for NDE applications.

The next most complicated configuration, Fig. 1.2 would be to put some impedance matching films on the transducer surfaces. If you can be reasonably sure about the kind of bond you're making between the film and transducer, then, this would be an acceptable situation and one that could be very well characterized under the condition of radial mode damping.

The next most complicated configuration is that of Fig. 1.3 which is getting close to what you think of as a typical NDE ultrasonic transducer. Because there is an impedance mismatch between the transducer and the water, implying a narrow band response, we try to acoustically load the piezoelectric element to get a wider band response. One way to do that, of course, is to simply impedance match the transducer with some lossy backing material. However, since the transducer material impedance is about 34 or 35, and water is 1.5, a majority of the input energy goes into the backing material. Increased insertion loss, or conversion efficiency, is traded for wider band width. This is a satisfactory configuration as long as you very carefully bond the transducer to the backing region or somehow arrange for there to be no bond at all. For example, if we just poured an epoxy composite onto the transducer and had it stick, this would satisfy that condition. We have been thinking about plating silver onto lithium niobate or a metallized region of lithium niobate, in order to provide a good impedance match.

In the configuration of Fig. 1.4 we begin to get to a more realistic situation where the backing material must be bonded to the transducer. We have constructed such a transducer and I have some results to report. We first looked for backing materials that might match lithium niobate and/or PZT. We found one which looked rather promising to us, and that was cast iron. At 5 MHz cast iron has the right mechanical impedance, sufficient propagation loss of 4 db per microsecond and is an electrical conductor. With an inch or so of the material, multiple reflections were well damped. We chose as a fabrication process, first of all, to metallize the disk with aluminum to a thickness of about 4000 Ångstroms. We did that for two reasons. First, we wanted to characterize the disk as a free resonator element without any loading other than air. The second reason is that we wanted a definite conducting plane to make electrical contact with the conductive epoxy used as bonding agent. Thus, if the conducting epoxy wasn't uniformly conducting, at least the metallized region on the disk served as a highly conducting plane, insuring uniform displacement current flow.

I'll give some results on what happened with that structure after briefly discussing the configuration in Fig. 1.5. The device is getting more complicated and consequently more parts are apt to fail or not work correctly. This is probably closer in detail to what you would find in a commercial transducer. There is some type of wear plate which is often put over the piezoelectric element to protect the metallization. It's there for a reason, as we found out when we scraped the metal off the front of our transducer; but nevertheless, it adds some complications. You now have the existence of yet another bond, and possible bond failure, between the wear plate and the piezoelectric element. Further, the acoustic interaction gets more complicated, and as we will show from our calculations, the transducer's response is very sensitive to the physical constraints on that construction.

In Figure 2 we show the electrical evaluation of our transducers. First, the free resonator lithium niobate disk is given on the left-hand graph. It has the near classic resonator response with the exception of some radial mode resonances. The radial resonances are fairly typical even with PZT. In some cases the PZT is much worse than this. In any case, these will typically be very high order modes of the radial motion.

The nice feature of free plate resonance measurements is that you can obtain an accurate check on the electromechanical properties of the piezoelectric material. You begin by taking a metallized disk, being sure it's very flat and parallel, and then measuring the parallel resonant frequency. That gives you a check on the velocity, or if you believe the velocity and are not sure about the thickness, it gives you a check on the thickness. Next, you examine the series resonant frequency and from that calculate the coupling coefficient, or k^2 of the material.

On the right side of Fig. 2 we have the case of the disk "bonded" to backing material, and immersed in the water. One of the things that first becomes apparent in comparison to the unloaded response is that the radial modes have been pretty much dampened. The ripple that you do see is probably due to the finite extent of the backing. It wasn't quite as thick or as long as it should have been. The other obvious thing is that the Q is drastically reduced. Since the Q is simply related to the slope of the phase at the resonance point, the Q of the loaded case is clearly much lower than the unloaded case discussed previously.

We did an analysis of what happens when you put a finite bond thickness between the transducer and its backing medium and keep the front surface unloaded for increased sensitivity. What we looked at is the radiation resistance, Fig. 3, the real part of the impedance, since it is very directly a measure of the transducer's radiating capability through the bond region. The plot is shown as a function of frequency for bond thickness in increments of 10 microns. Initially we did not know the mechanical characteristics of the epoxy. Thus, it was necessary to do some empirical curve fitting of the experimental results in order to determine those characteristics. It turned out that we had an apparent bond thickness of 0.004 inch, about like a sheet of paper. At 5 MHz, as you can see from the narrow band response, this was reasonably disastrous. It says a couple of things: first, be careful about the bond thickness and thickness uniformity. And second, by simply bonding a transducer to a known medium and then measuring the radiation resistance, you get a very good indication of how well that bond has been formed. You can use this data to evaluate a fixed transducer or the characteristics of the bond region. Our experimental results are shown in Fig. 4. The top most curves are for air loading on the front face, and the bottom curves are for water loading. The smooth curves are theoretical.

It turns out computationally that the peak of the radiation resistance is very sensitive to the impedance of the bonding region, and its location in frequency is very sensitive to the thickness-velocity ratio of the bond region. Thus, by adjusting those parameters we obtained an empirical fit as

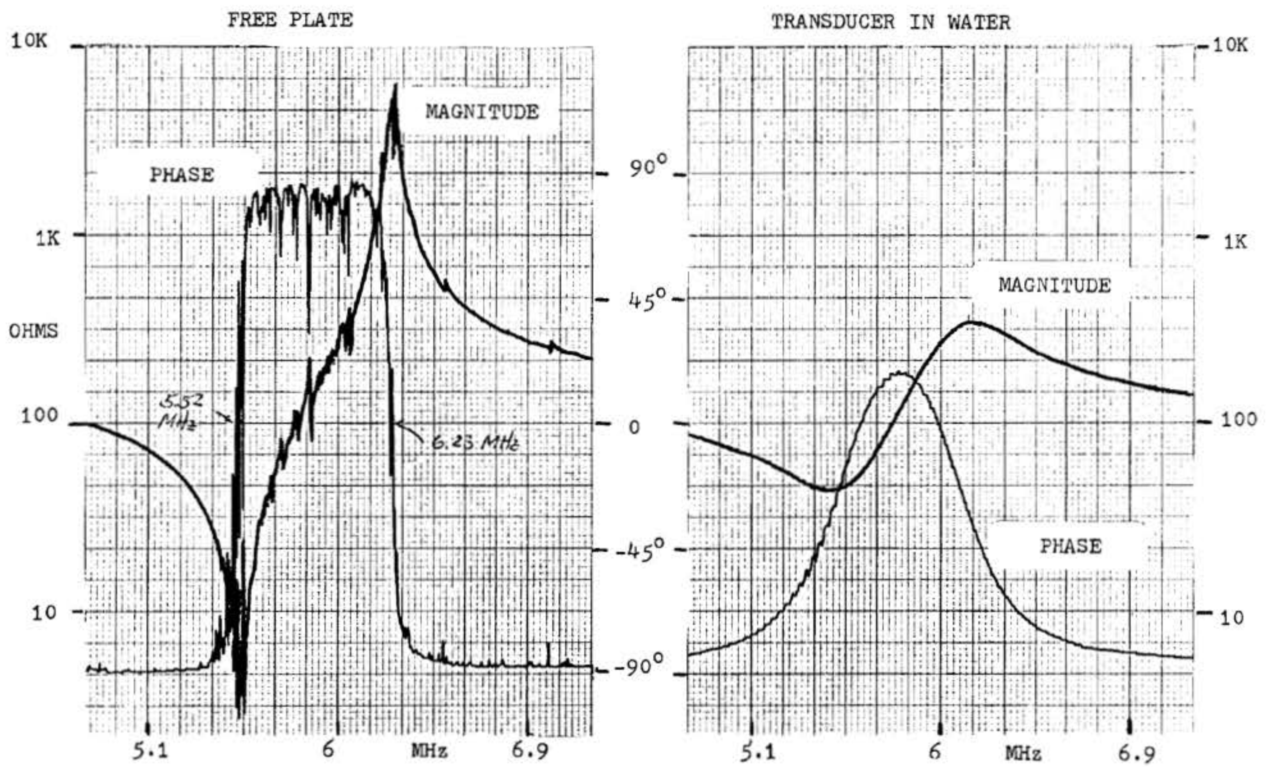

Fig. 2. Magnitude and phase of electrical impedance of free plate disk and loaded transducer consturcted from loaded disk.

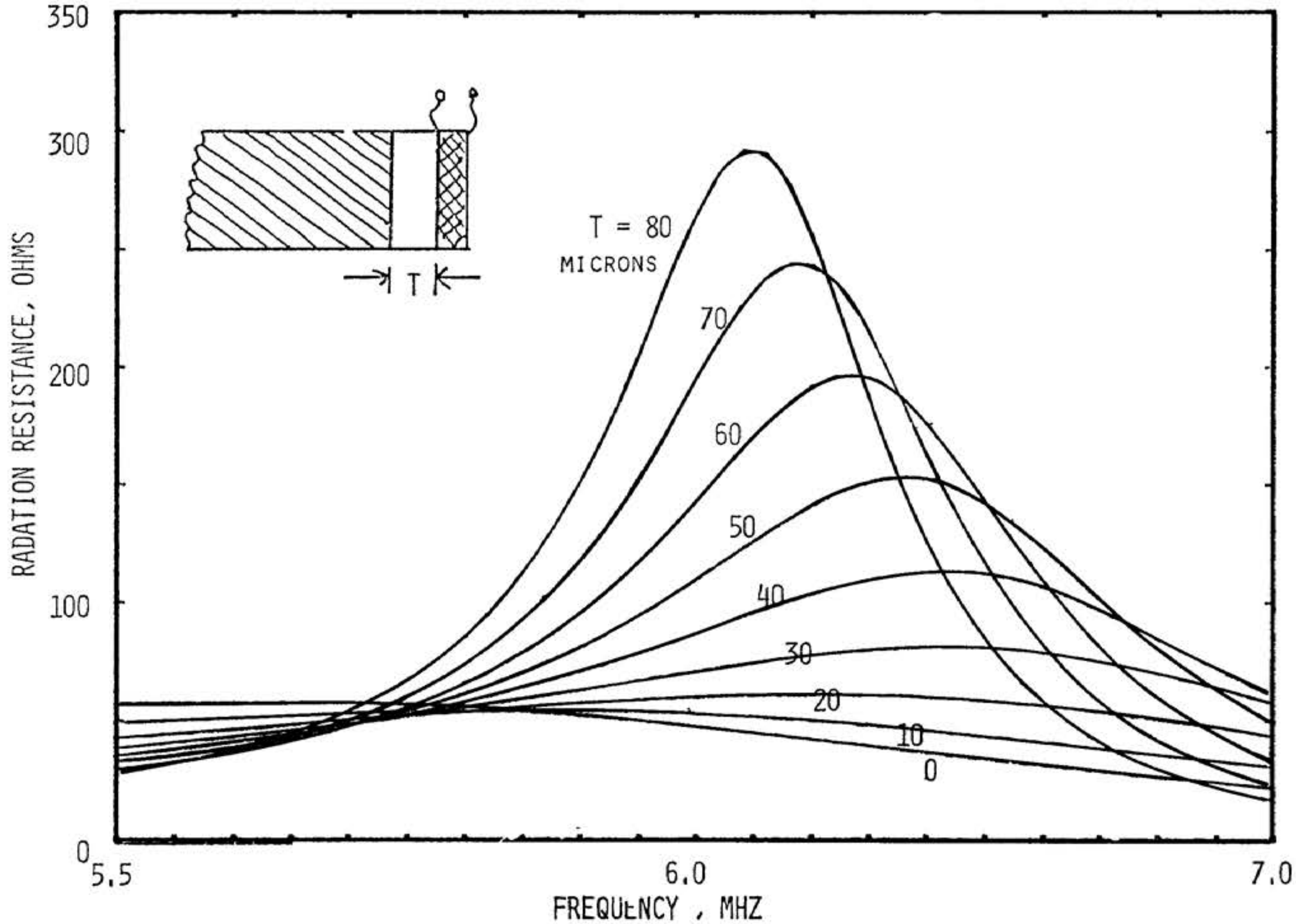

Fig. 3. Radiation resistance versus frequency, $LiNbO_3$, epoxy bond, cast iron backing.

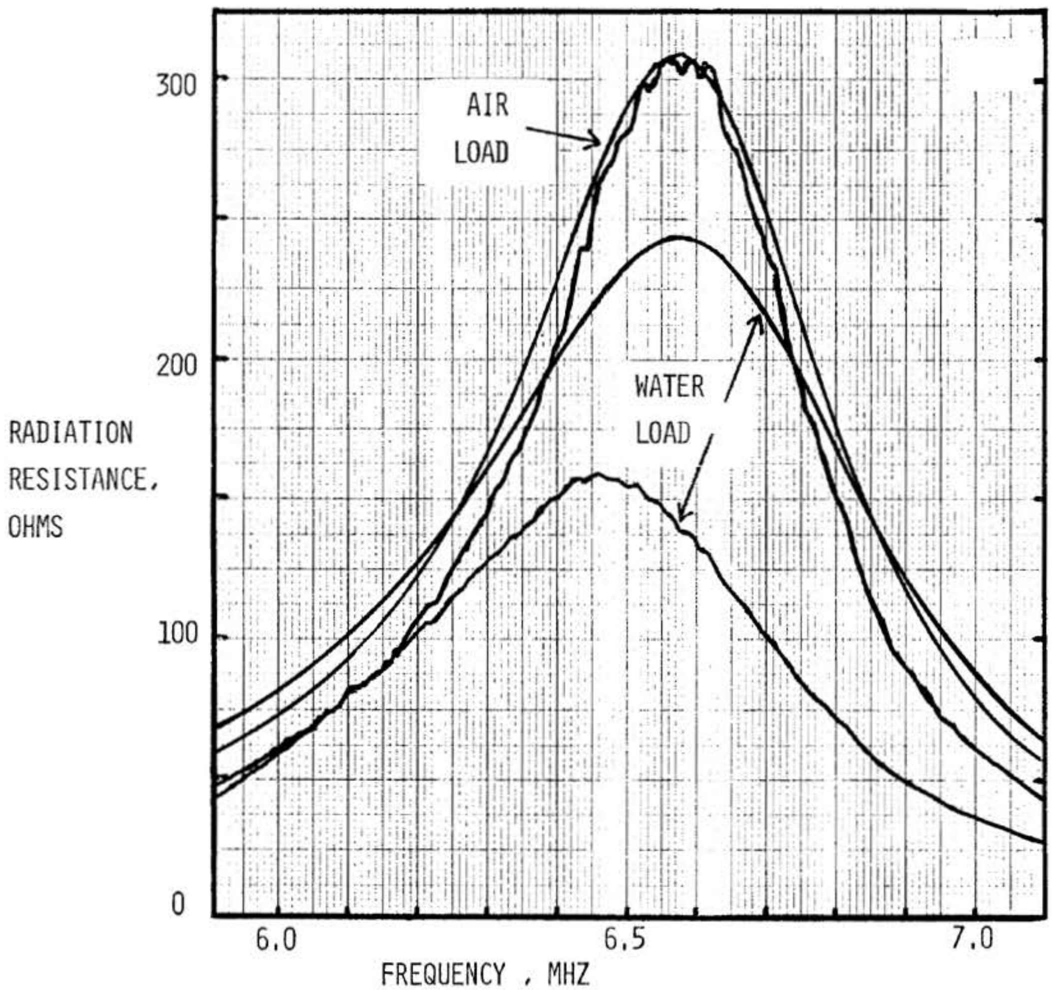

Fig. 4. Radiation resistance versus frequency, theory, smooth curve, experiment rough curve.

shown. Then we calculated what the response would be for water loading and obtained the lower theoretical curve, somewhat above the experimental cases. The experimental curve is lower due to the effect of shunt capacitance. The disk in air has a capacitance of 100 pF, but when placed in water, with the "hot" electrode exposed, the water adds a very significant shunt capacitance. Only 20 pF shunt capacitance are required to account for the observed effect.

Fig. 5 shows the transducer circuit models used for the previous analysis. These are the straightforward Mason models coupled to transmission lines. The simple transmission line segments are used to model bond regions. The lossy backing load was modeled by an infinite length transmission line subsequently replaced by a lumped impedance. The front load was treated similarly. In general, we can put in as many transmission line sections as necessary to describe any given transducer construction.

The previous remarks have been concerned with electrical measurements. We have also studied the wave phenomena exterior to the transducer in order to determine field patterns. Our primary reason for doing this is transduction analysis. We have developed computer codes for examining the far field or not too far field in both magnitude and phase and then used this information to determine the amplitude distribution at the transducer. From such quantitative amplitude and phase information, known as a function of frequency and spatial position, one can accurately determine the nature of the wave incident upon a target flaw.

The experimental apparatus used to obtain this information is shown schematically in Fig. 6. We do all measurements in a sinusoidal steady state because we're interested in magnitude and phase. We use a standard Hewlett Packard network analyzer as a phase-locked detector in this case. The network analyzer measures the amplitude and phase of an unknown test signal relative to a known reference signal. The reference signal may be obtained directly from the signal generator or from an indirect source, such as another transducer or propagation path. In general, the ratio of test to reference signals is determined as well as the relative phase. The analog amplitude and phase information is displayed in analog form by the network analyzer for quick reference and also sent to the Laboratory Peripheral System, LPS, for digital conversion and processing by the PDP-11 computer. The computer is also used to generate and send commands to the numerical controller, which in turn drives the XY table used for positioning the probe transducer.

Figure 7. This is an example of a probe result for two 1/2 inch diameter transducers scanned against each other about a half an inch apart. The dynamic range available on the instrument is shown to be about 80 to 90 db. Input power levels here are of the order of minus 10 dbm. Figure 8 shows a two-dimensional plot of the amplitude of a 0.5 inch transducer sampled by a 0.11 inch transducer separated by a distance of 6 inches at a frequency of 5.8 MHz (wavelength 10 mils). The area sampled is a square with 1.2 inch sides.

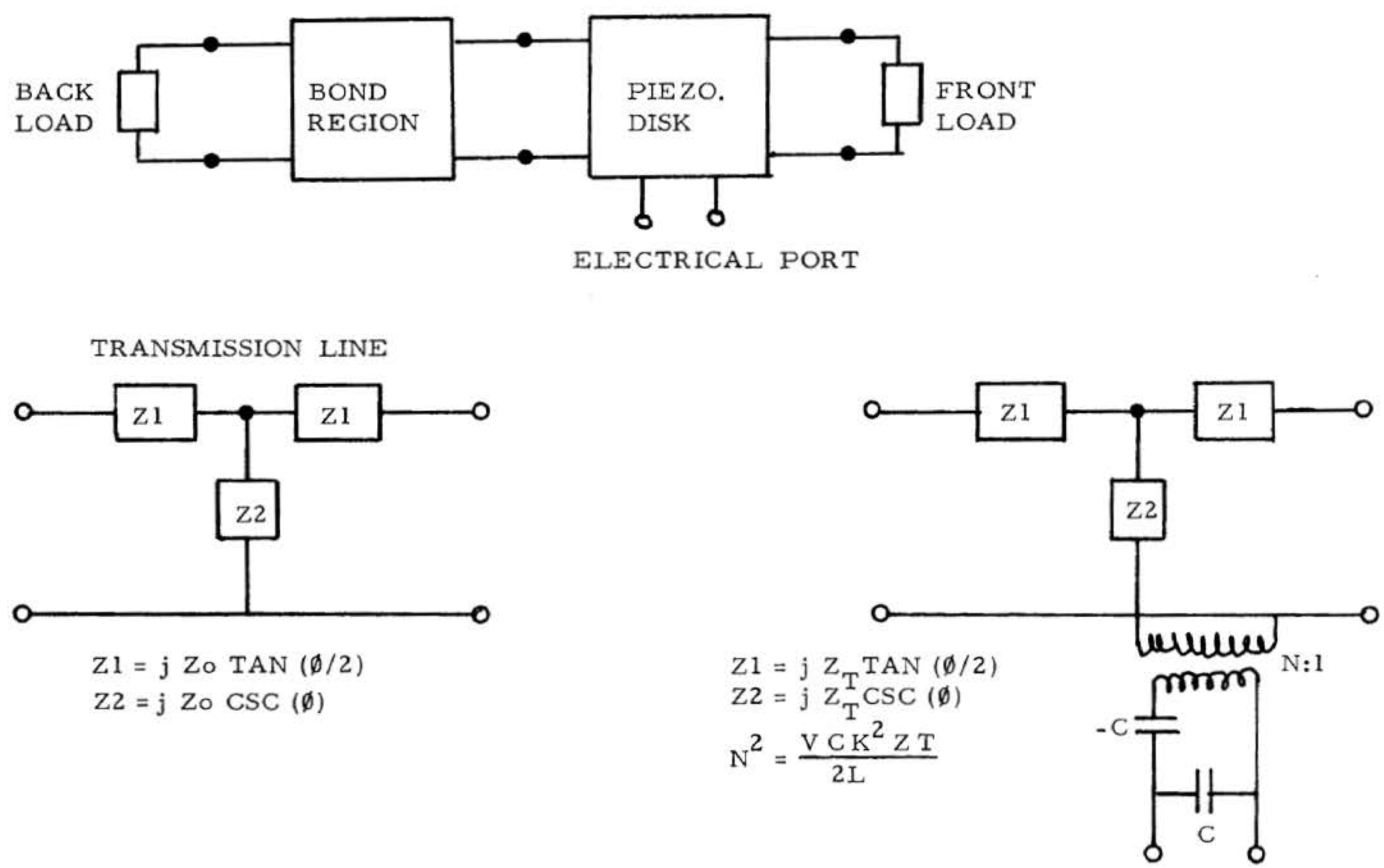

Fig. 5. Transducer model and load coupling.

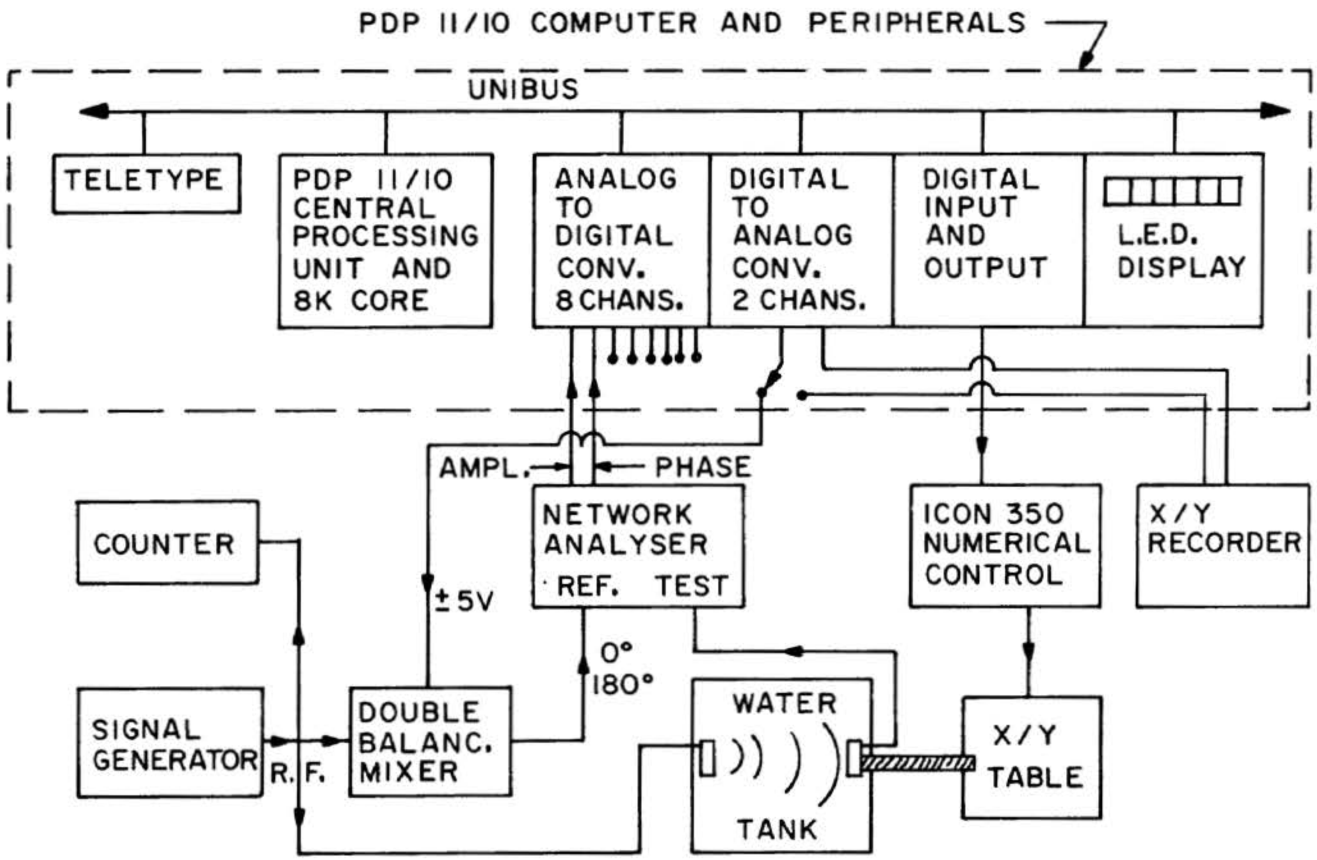

Fig. 6. Schematic diagram of field scanning system.

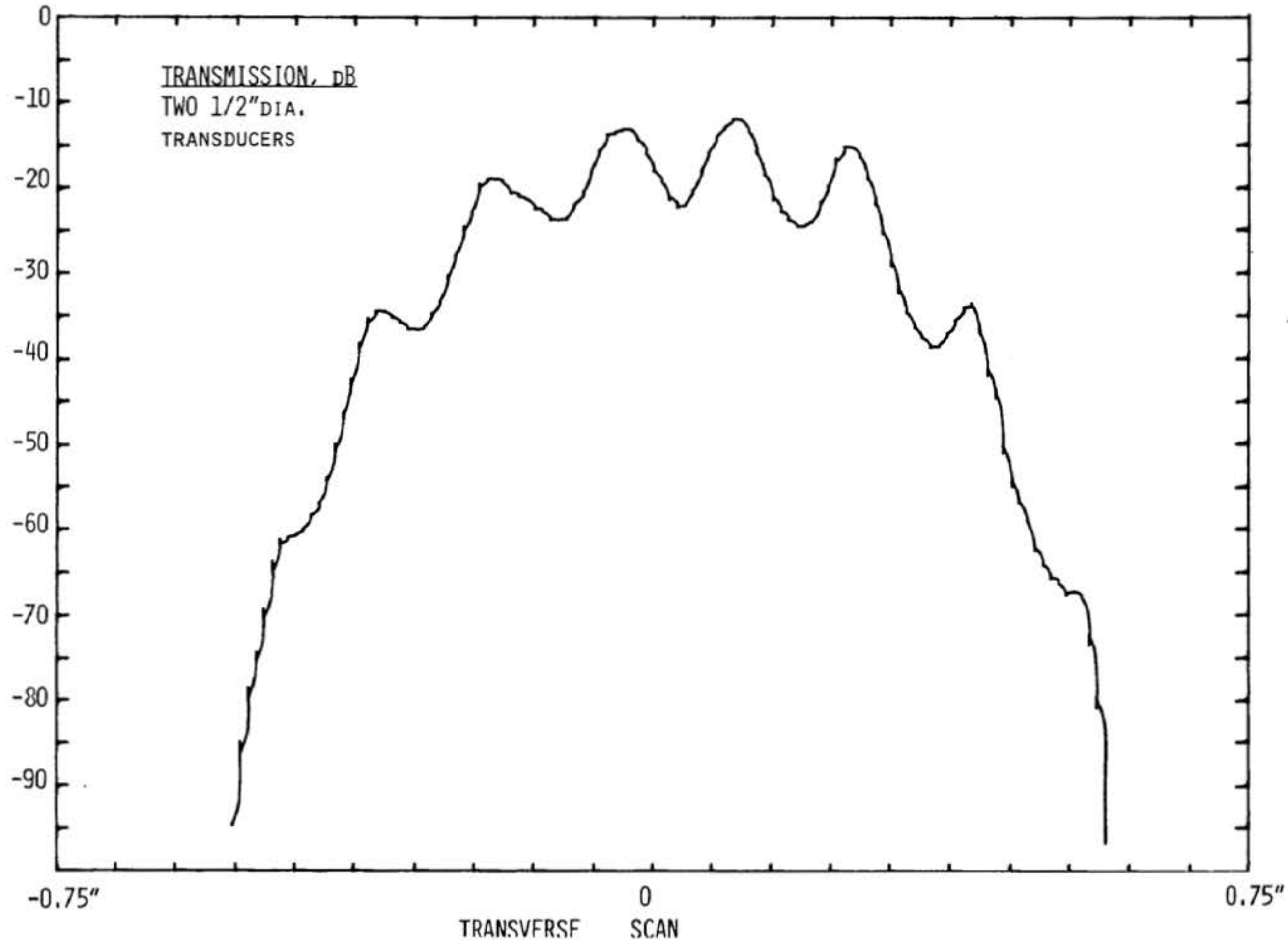

Fig. 7. Amplitude in dB vs transverse scan for 5 MHz transducers spaced 1/2 inch.

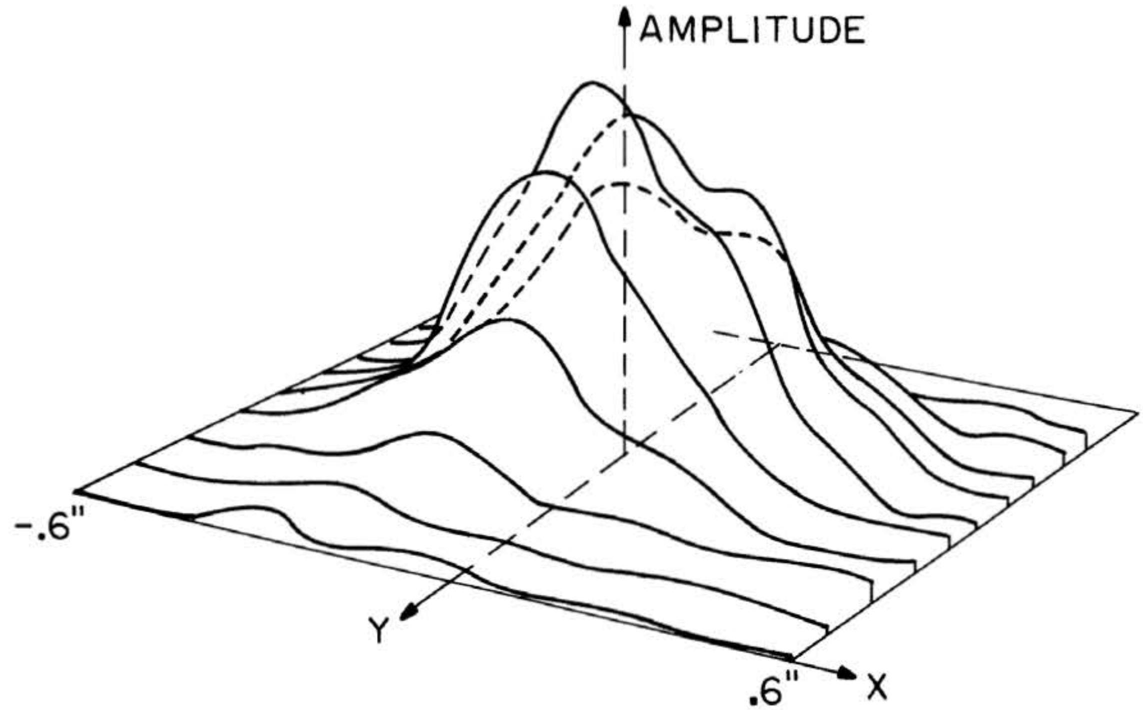

Fig. 8. Amplitude of 0.5 inch transducer sampled by a 0.11 inch transducer.

DISCUSSION

DR. HENRY BERTONI: Are there any questions on this paper?

DR. WOLFGANG SACHSE (Cornell University): On the vertical axis you always plotted a power level or a voltage. Do you know exactly what that corresponds to in terms of some mechanical kinematical variable, pressure or velocity or displacement or strain or what?

PROF. LAKIN: No, not as yet. That means having to calibrate the transducer. What we'd like to be able to do is to establish a transducer where we can tell how much acoustic sound intensity is obtained for a given electrical input. In any case when you do a scattering measurement, except for optical probing, you're always working in the electrical world. You send a pulse into your transducer, an electrical pulse, and you get an electrical pulse out. The only thing that's really of interest is that transfer function.

DR. SACHSE: But when we're making comparisons with theory, the theory can calculate for us what the mechanical kinematical variables will be, what the velocity will be, what the stresses will be or something. So, now we ask what does our transducer really measure.

PROF. LAKIN: Are you talking about scattering measurements?

DR. SACHSE: Any measurements.

PROF. LAKIN: Okay. Just scattering is always relative, right? You get so much back for so much in.

You don't? Not--if the system is nonlinear, no.

PROF. YIH HSING PAO (Cornell University): I keep asking the kind of question that ne could not answer satisfactorily. Suppose I stick a transducer to a surface of a plate. I generate the pulse; I receive a pulse, okay? The pulse runs through the plate, runs through a defect, and comes back.

PROF. LAKIN: Sure.

PROF. PAO: What did that really pick up from this mechanical medium? Did I pick up the stresses on the surface, or the transducer, or pick up the velocity? Someone told me it's displacement, but I don't believe it. Or do we pick up energy? What do you pick up from all the scattered signals, the reflected signals?

PROF. LAKIN: Our concern is only what goes out of the transducer and what comes back in. In fact, we model without regard to the standing wave effect.

DR. HAROLD FROST (AFCRL): Did you mount either transducer within a bridge to compensate the capacitance in there?

PROF. LAKIN: You mean as far as matching?

DR. FROST: No, because, you see, then you can get a signal which is proportional to multiple current or something, and it gives you a definite relationship to acoustic parameters.

PROF. LAKIN: Well, we think if we can measure the phase of the voltage and current out of the transducer, you'll get that same information.

DR. FROST: Except that everything else will be mixed up with it.

PROF. LAKIN: Well, we should be able to sort that out, if you have an analytic characterization of that transducer.

DR. VINCE HORVATH (Bethleham Steel Corporation): One thing that's mentioned in the literature and I think it was brought out earlier this morning, is that the transfer function from the transducer to acoustical waves as a receiver is not necessarily the same as a transfer function in the reverse direction. So, you can't necessarily have a unique transfer function.

PROF. LAKIN: The circuit models are okay, given the same sound intensity and the same beam distribution. You may, however, send out a wave and get something back that's not of the same type wave front in which case the transfer function wouldn't be the same. But if the kind of wave that is coming in is the same that goes out, then, S_{12} is S_{21} and the two transfer functions are the same.

DR. HORVATH: Of course, it will be based upon the reciprocity principle, but not necessarily true because of the nonlinearities in the intensity. If you're trying to answer these people's questions, you have to take that into account. Because the wave coming back from a scattered signal is not going to be the same intensity as the wave going out from the transmitter.

PROF. LAKIN: Well, it doesn't really have to be as long as it is linearly related to the output amplitude and it's the same type of beam.

PROF. VERNON NEWHOUSE (Purdue University): Excuse me. I was the guy who mentioned that the transfer function wasn't the same, but I meant a very simple thing by that. I merely meant that if you have, say, an R in series with a C, then the electrical transfer function going the other way in a very simplistic sort of way. Thus, as long as you model the transducer in the way that is done with electrical components, this is taken into account automatically by the electrical equivalents.

PROF. LAKIN: And those electrical components show that S_{12} is S_{21}.

DR. HORVATH: Assuming linearity.

PROF. LAKIN: Assuming linearity, yes.

DR. GREEN (Johns Hopkins University): I would like to suggest that if you do get the opportunity to open some commercial transducers, and that even if you can't do that, go visit some commercial manufacturers, because I feel that some of the trouble with the commercial transducers we're buying nowadays is really the way they're made by the manufacturer. Because they don't obey the general--I don't want to make general statements, they don't always do that--but in some cases they don't follow the general simple rules of physics or electrical engineering.